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Acceleration of charged particles by electrostatic ion-cyclotron waves in the presence of parallel electric field and ion beam-particle aspect analysis. II

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Abstract : The acceleration of charged particles by electrostatic ion-cyclotron waves has been studied using the trajectories of the charged particles in the presence of parallel electric field and ion beam. The waves propagating at an angle to the geomagnetic field are considered. The plasma in the acceleration region is supposed to be composed of two types of charged particles, the non-resonant particles of the background plasma and the resonant particles participating in the energy exchange with the wave The density perturbation and the particle velocities due to the presence of wave are considered to estimate the energy provided to the accelerating particles The energy transferred to the particles by the wave along and perpendicular to the magnetic field are estimated for the auroral acceleration region.

Keywords : Ion-cyclotron waves, acceleration, wave-particle interaction, auroral acceleration region.

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1. Introduction

Recently, the electrostatic ion-cyclotron instability has been studied, investigating the trajectories of the charged particles in the presence of parallel electric field and ion beam [1]. The effects of parallel electric fields are incorporated through the modification of distribution function which is anisotropic Maxwellian. The stabilising/destabilising effects by the parallel electric fields have been studied, pertaining to simultaneous observations of electrostatic ion cyclotron waves and parallel potential drop in the auroral acceleration region. The effects of energetic ion beam on the wave generation processes have been investigated which, may be a possible cause for the electrostatic ion cyclotron wave generation due to the upward flowing ion beams [1].

Since the initial observations of electrostatic ion-cyclotron (EIC) waves, there has been much discussion concerning possible free energy sources needed to derive the waves [2]. Kintner *et al* [3] considered the possibility that either electron drift or upstreaming ions (ion beams) were the source of free energy for the EIC waves observed from S3-3 satellite data. In a statistical study of S3-3 data, Cattell [4] concluded that an ambiguous identification of free energy source for the waves observed by Kintner *et al* [3] was not possible, and the waves could be driven by a combination of ion beams and electron drifts (field aligned currents). In subsequent work, Kaufmann and Kintner [5] concluded that many features of the S3-3 data could be understood if the observed EIC waves were being driven by ion beams rather by cold drifting electrons. This view is supported by theoretical and numerical analysis of Okuda and Nishikawa [6]. However, Bergman's [7] results indicate that the relative importance of two processes is sensitive to temperature regime, $T_e \sim T_i$, the current driven ion cyclotron instability modified by the presence of an ion beam appears to be most likely mechanism for explaining the S3-3 wave data. Laboratory experiments on ion cyclotron turbulence [8] showed that ion heating results in a low density warm core surrounded by a denser hot ion cloud. Therefore, a high level ion cyclotron turbulence can be sustained in a core of ion gyroradius scale. Thus, it is possible for an unstable field aligned current to produce fine structures in an unstable field aligned region and lead to the formation of auroral arcs embeded in the inverted-V precipitation region.

The mechanism that produces the inverted-V electron distribution and consequently the aurora is a quasi-static, parallel to the magnetic field electric field. The signatures of such a parallel electric field are well known. They include the inverted-V itself [9–13], the detailed electron and ion distributions, which include upflowing ion beams and electron trapped between the potential and the mirror point and electrostatic shocks [12]. However, not all features of auroral particle distributions can be explained by such quasistatic electric fields Outside of inverted-V's features of auroral particle acceleration such as field aligned counter streaming electrons [13, 14], conics [15,16] and supra-thermal electron bursts [17] are difficult to explain by quasi-static electric fields.

A description of the auroral potential drop should consider the large scale dynamics of the auroral zone as well as the microsopic processes which can directly produce parallel electric fields. In the auroral ionosphere, a large electric field has been reported where Langmuir soliton like structures have been measured, contains plasma frequency oscillations as large as 500 mV/m, the envelops of which have parallel electric fields of 100 mV/m lasting for a fraction of millisecond. The auroral acceleration region where electrostatic shocks have been measured contains perpendicular fields as large as 1000 mV/m and parallel fields as large as 100 mV/m where double layers having parallel fields upto 10 mV/m are reported [18].

At very low frequencies $\omega <, 2\Omega_i$ $E_{\parallel}$ shows a higher power than $E_{\perp}$ imploying that $E_{\parallel}$ has a quasi steady component, as expected, such DC fields appear across the double layer inside the current sheet. In the frequency range $2\Omega_i \sim \omega < \omega_{lh} \sim 6\,\omega_i$, the power in $E_{\perp}$ is larger than that in $E_{\parallel}$ by a factor < 5. However, it is seen that near $\omega = \Omega_i$ the spectral power is enhanced in both $E_{\parallel}$ and $E_{\perp}$. EIC waves at higher harmonics and waves near the lower hybrid frequency with relatively short wave lengths are expected to be excited in the sheet.

In the previous paper [1], we have investigated the effect of parallel electric fields and ion beam on the electrostatic ion-cyclotron instability. The stabilizing/destabilizing effects by parallel electric fields and ion beam are widely investigated using particle aspect analysis. Using same methodology and mathematical analysis the heating and acceleration of charged particles, parallel and perpendicular to the magnetic field are analysed and discussed for the auroral acceleration region.

2. Basic assumptions

We consider a homogeneous collisionless plasma in a uniform magnetic field B_0 along the Z-direction. The ions are supposed to have unit charge. It is assumed that an electrostatic ion-cyclotron wave in the form below, starts at time $t = 0$ when the resonant particles are not yet disturbed. We assumed a wave for the form :

$$\boldsymbol{k} \parallel \boldsymbol{E}\ , \ \boldsymbol{k} = (k_\perp, 0, k_\parallel)$$

and $$E = (E_x, 0, E_z) \tag{1}$$

with

$$E_x(\boldsymbol{r}, t) = E_1 \cos(k_\perp x + k_\parallel z - \omega t) \tag{2}$$

$$E_z(\boldsymbol{r}, t) = \kappa E_1 \cos(k_\perp x + k_\parallel z - \omega t)$$

where $$\kappa = \frac{k_\parallel}{k_\perp} \tag{3}$$

The amplitude E_1 is thought to be a slowly varying function of t that is $\frac{1}{E_1}\frac{dE_1}{dt} << \omega$. ω is the frequency of EIC wave, $k_\perp$ and $k_\parallel$ are components of the wave vector perpendicular and parallel to B_0.

Using the basic equation of motion and trajectories of free gyration, the perturbed velocities and perturbed densities for resonant and non-resonant particles associated with the wave have been derived by Bajaj and Tiwari [1], and charge in energy density for resonant particles is derived as :

$$W_{i\perp} = \left[\frac{\lambda E_1^2}{8} \frac{\omega_{pi}^2}{\Omega_i^2} \frac{1}{2} \left\langle J_0^2 + J_2^2 \right\rangle \frac{\Omega_i}{\omega} \frac{\omega}{k_\parallel V_{\mathrm{Th}i}} \frac{\Omega_i t}{(2\pi)^{1/2}} \right]$$
$$\left[1 - R \frac{\left(\frac{\Omega_i}{\omega} + \frac{V_D}{V_\phi} - 1 \right)}{(\Omega_i/\omega)} \cdot \frac{T_{\perp i}}{T_{\parallel i}\left\{ 1 + \frac{e^2 E_\parallel^2}{k_\parallel^2 K^2 T_\parallel^2} \right\}} \right] \times$$
$$\frac{\exp -\left[\omega^2 \left\{ 1 - \frac{\Omega_i}{\omega} - \frac{V_D}{V_\phi} \right\}^2 \Big/ \left\{ 2 k_\parallel^2 V_{\mathrm{Th}i}^2 \left(1 + \frac{e^2 E_\parallel^2}{k_\parallel^2 K^2 T_{\parallel i}^2} \right) \right\} \right]}{\left\{ 1 + \frac{e^2 E_\parallel^2}{k_\parallel^2 K^2 T_{\parallel i}^2} \right\}^{1/2}} \tag{4}$$

and

$$W_{r\parallel} = \left[\frac{\lambda k_\perp^2}{8}\frac{\omega_{pi}^2}{\Omega_i^2}\Omega_i l \frac{\omega}{k_\parallel V_{\mathrm{Thi}}}\frac{1}{2}\left\langle\left(J_0^2 + J_2^2\right)^2\right\rangle\frac{T_{\perp i}}{T_{\parallel i}}\right]$$
$$\left[\left(1 - \frac{\Omega_i}{\Omega} - \frac{V_D}{V_\phi}\right)^2 \Big/ \left(\frac{\Omega_i}{\omega}(2\pi)^{1/2}\right)\right]$$
$$\frac{\exp - \left[\omega^2\left\{1 - \frac{\Omega_i}{\omega} - \frac{V_D}{V_\phi}\right\}^2 \Big/ \left\{2k_\parallel^2 V_{\mathrm{Thi}}^2\left(1 + \frac{e^2 E_\parallel^2}{k_\parallel^2 K^2 T_{\parallel i}^2}\right)\right\}\right]}{\left\{1 + \frac{e^2 E_\parallel^2}{k_\parallel^2 K^2 T_{\parallel i}^2}\right\}^{3/2}} \tag{5}$$

where

$$< J_l^2 > = \int_0^\infty 2\pi V_\perp dV_\perp J_l^2\left(\frac{k_\perp V_\perp}{\Omega_i}\right) f_\perp i(V_\perp)$$
$$= \exp\left(-\frac{1}{2}k_\perp^2\rho_i^2\right) I_l\left(\frac{1}{2}k_\perp^2\rho_i^2\right) \tag{6}$$

and ω_{pi} is the ion-plasma frequency, Ω_i is ion-cyclotron frequency, V_{Thi} is the ion thermal velocity, V_D is ion beam velocity, V_ϕ is the phase velocity of the wave, K is Boltzmann constant, $T_{\perp i}$ and $T_{\parallel}$ are the components of ion temperature perpendicular and parallel to B_0, J_l is the Bessel function and I_l represents the modified Bessel function, and

$$R = \frac{\left\langle(J_{l-1} + J_{l+1})^2\right\rangle}{\left\langle\left(J_{l-1}^2 + J_{l+1}^2\right)\right\rangle} \tag{7}$$

$f_{\perp i}(V_\perp)$ represents the perpendicular component of the anisotropic Maxwellian distribution function. ρ_i is the ion gyroradius.

3. Results and discussion

The heating of ions by electrostatic ion cyclotron instability has been considered in several papers using various approaches. Dakin *et al* [19], considered the heating of ions and the anamolous resistivity using a quasi-linear approach. They found that the heating in the perpendicular direction was orders of magnitude larger than the heating in the parallel direction. The perpendicular heating has contributions from the interaction of waves with resonant particles.

The resonant particles energy perpendicular to the magnetic field $W_{r\perp}$ is plotted versus Ω_i/ω for different $E_\parallel$ in Figure 1, which shows that resonant particles energy $W_{r\perp}$ decreases with the increases of Ω_i/ω and approaches to zero for higher values of Ω/ω. The parallel electric field enhances the $W_{r\perp}$. Thus the perpendicular acceleration may be possible by parallel electric field through the ion cyclotron instability. This is pertaining to the results reported by Klumpler [20] and Singh *et al* [21]. The ion cyclotron waves serve the purpose of transferring electrostatic energy to the heating of ions perpendicular to the magnetic field. Heating efficiency is maximum as Ω_i/ω approaches to 1 for the first harmonic of the wave.

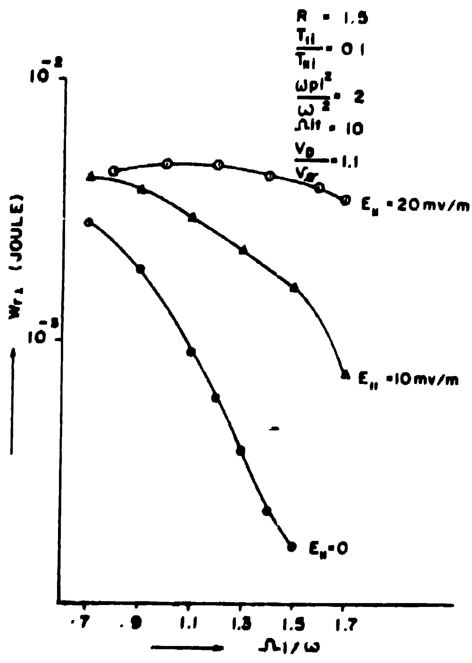

Figure 1. Variation of $W_{r\perp}$ (Joule) with Ω_i/ω for different values of $E_\parallel$.

The enhancement of $W_{r\perp}$ of resonant particles with V_D/V_ϕ due to different $E_\parallel$ is shown in Figure 2. The effect of parallel electric field is to enhance the heating of ions perpendicular to the magnetic field. The heating of ions is maximum as the phase velocity V_ϕ is around the beam velocity V_D but at the larger deviations, the heating efficiency decreases. The large deviation of beam drift velocity with phase velocity of the wave may reduce the energy exchange of the wave [11] where, the EIC waves are possible for $V_D/V_\phi \sim 1$. Bajaj and Tiwari [11] have also predicted that the electric field reduces the growth rate as $V_D/V_\phi \sim 1$. Thus, the energy given up by the wave goes to the heating of ions perpendicular to the magnetic field. Here wave was generated by the free energy contained in the beam velocity of ions. Thus maximum energy exchange to the ions is possible, when V_D approaches to phase velocity of the wave V_ϕ and wave growth is possible by parallel electric fields as V_D is much higher than V_A..

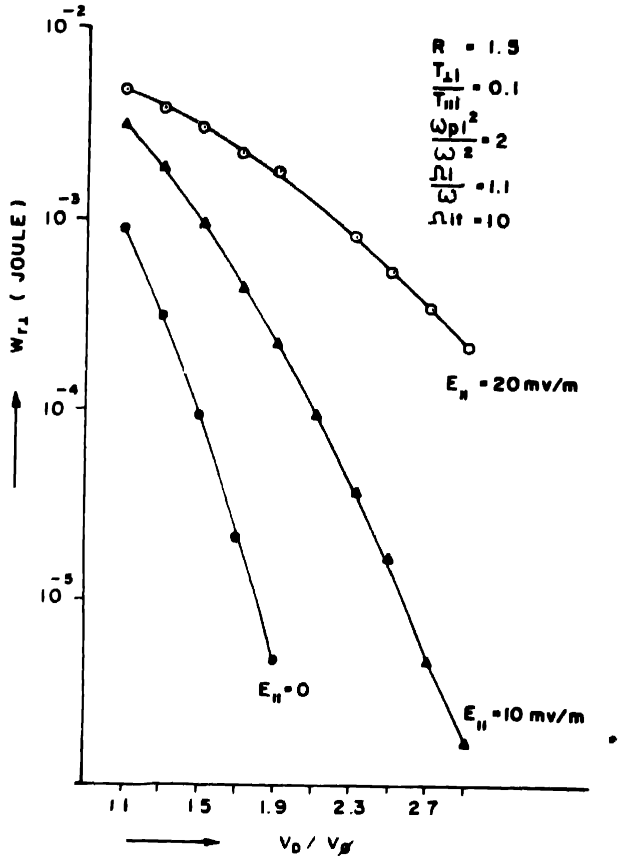

Figure 2. Variation of $W_{r\perp}$ (Joule) with V_D/V_ϕ for different values of $E_\parallel$.

The perpendicular resonant particles energy due to the wave depends upon time as given by eq. (4). The increase in perpendicular heating occurs as particles stay for a longer time in the field of ion cyclotron wave (Figure 3). Upto the particular values of $\Omega_i t \approx 50$, the $W_{r\perp}$ increases rapidly followed by a slower increase. The rapid rise is associated with the first stage instability caused by the shorter wave length mode $k_\perp \rho_i \sim 1$ and the slower increase in $W_{r\perp}$ is accompanied by the second stage, which may be non-linear instability. Note that $W_{r\perp}$ is not saturated at $\Omega_i t \approx 190$ but the system may be close to the non-linear instability as the ions may be trapped in the potential of EIC wave. The downward electric fields along the auroral field lines and the geomagnetic mirror force may keep ions trapped in the region of perpendicular acceleration for a sufficiently long time, and thus the ions can be energised up to the observed energy levels [22]. The parallel electric field enhances perpendicular heating as the time of interaction increases. Several mechanism for the perpendicular acceleration or heating utilizing wave interaction (by EIC wave) have been proposed [23–27].

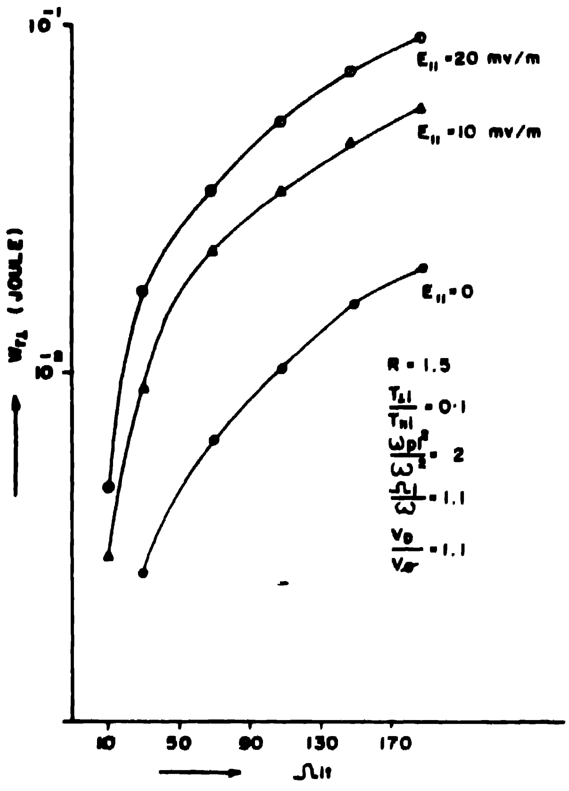

Figure 3. Variation of $W_{r\perp}$ (Joule) with $\Omega_{i\dagger}$ for different values of $E_{\parallel}$

Now we illustrate the parallel acceleration of upflowing ions. The change of resonant particles energy along the magnetic field $W_{r\parallel}$ has been plotted versus Ω_i/ω in Figure 4 for different $E_{\parallel}$. The $W_{r\parallel}$ increases with increase of Ω_i/ω and for higher values of $\frac{\Omega_i}{\omega}$ (>1), it decreases rapidly.

The parallel electric fields expand the band of frequency. When the frequency of the wave is very much less than the ion cyclotron frequency, the $W_{r\parallel}$ may approach to zero. Figure 5 shows the variation of parallel resonant particle energy $W_{r\parallel}$ versus V_D/V_ϕ for different $E_{\parallel}$. Here we have considered only first harmonic of ion cyclotron frequency. When the phase velocity of the wave is very much less than the drift velocity of the ions, the $W_{r\parallel}$ may approach to zero. Hence it may be predicted that for the slight differences between phase velocity of the wave and drift velocity of the ions, there would be sufficient amount of resonant particles energy along the ambient magnetic field. Here also the $E_\parallel$ expand the bandwidth of $W_{r\parallel}$. Comparing the results of Bajaj and Tiwari [11] and Figures 2 and 5 one can predict that the electric field reduces the growth of ion cyclotron waves and simultaneously the parallel energy when the phase velocity is around the beam velocity and the energy given up goes for the acceleration of ions perpendicular to the magnetic field. Thus the perpendicular acceleration may be possible in the presence of electric field, ion drift velocity by the generation of ion cyclotron waves [23,24,28,29].

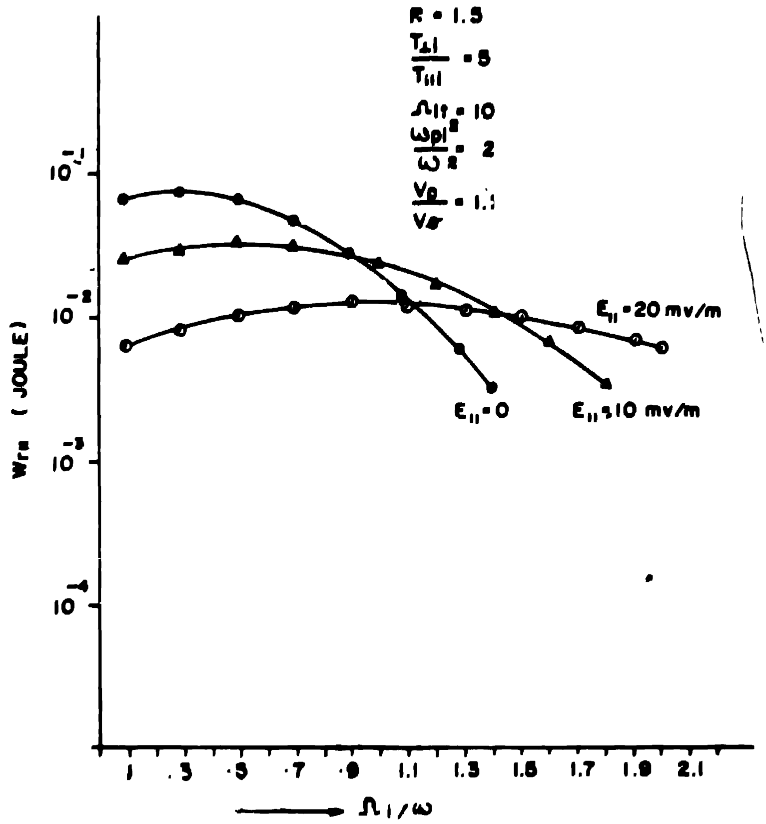

Figure 4. Variation of $W_{r\parallel}$ (Joule) with $V\Omega_i/\omega$ for different values of $E_\parallel$

The existence of upflowing ions with conical pitch angle distributions and perpendicular ion acceleration has been reported in the auroral acceleration region [24].

The perpendicular acceleration may be achieved through resonant wave particle interactions between the ions and the observed electrostatic ion cyclotron waves. The parallel acceleration may be accounted for by the observed small spatial scale large amplitude electric fields in shocks and large spatial scale, smaller amplitude, parallel electric fields present in regions of low frequency turbulence, upflowing ions and field aligned currents. The presence of ion beam and parallel electric field may be possible cause for the generation of EIC wave [1] in the auroral acceleration regions and perpendicular acceleration may be a possible effect.

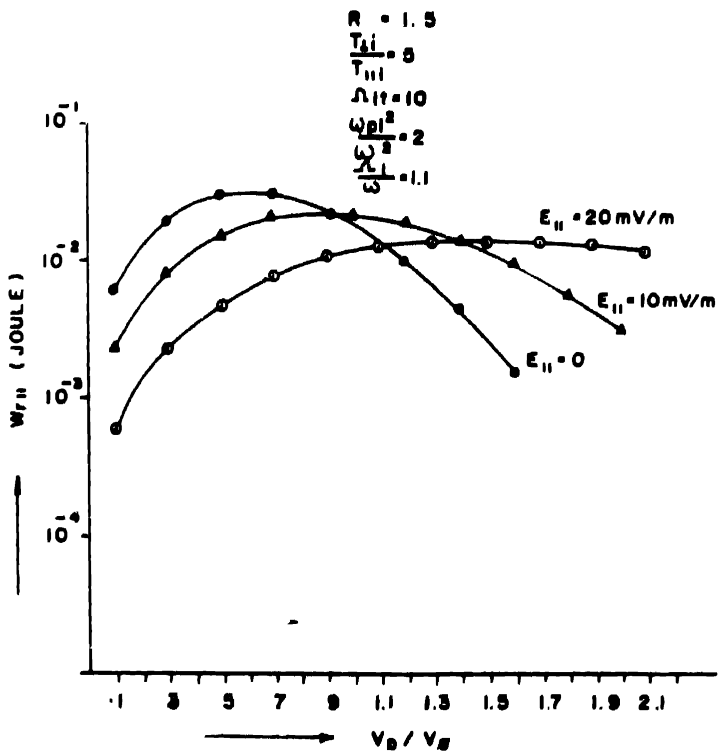

Figure 5. Variation of $W_{T\parallel}$ (Joule) with V_D / V_ϕ for different values of $E_\parallel$.

The perpendicular acceleration of resonant ions in our study is consistent with the characteristic of auroral ion conics when they are observed in the region where they are energised [30, 31]. The perpendicular acceleration of ions in the region of upward current is in agreement with satellite observations [32,33]. The wave particle interaction may cause the perpendicular acceleration and the energy of parallel potential drop is extracted through the ion cyclotron waves. Recent measurements of EIC waves using S3-3 satellite data near the regions of upward flowing ions [34] observations of EIC waves at lower altitudes (400–600 km) near ion transverse acceleration region [35–37], may be due to interaction of plasma particles and EIC waves in the presence of parallel electric fields. The study can also be utilised for laboratory plasma, ion heating in plasma confinement devices through the EIC waves and parallel electric fields.

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References

[1] V K Bajaj and M S Tiwari 1993 *Indian J. Phys* **67B** 343

[2] M L Alport, S L Cartier and R L Merlino 1986 *J. Geophys Res* **91** 1599

[3] P M Kintner, M C Kelley, R D Sharp, A G Ghielmetti, M Temerin, C A Cattell, P F Mizera and J F Fennell 1979 *J Geophys. Res* **84** 7201

[4] C A Cattell 1981 *J Geophys Res.* **86** 3641

[5] R L Kaufmann and P M Kintner 1982 *J Geophys Res.* **87** 10487

[6] H Okuda and K I Nishikawa 1984 *J. Geophys. Res* **89** 1023

[7] R Bergmann 1984 *J. Geophys Res.* **89** 953

[8] H Bohmer and S Fornaca 1979 *J Geophys. Res* **84** 5234

[9] L A Frank and K L Ackerson 1971 *J Geophys. Res* **76** 3612

[10] D A Gurnett 1972 *Electric Field and Plasma Observations in the Magnetosphere in Critical Problems of Magnetospheric Physics*, ed E R Dyer (National Academy of Sciences, Washington D C) p. 123

[11] C S Lin and H Hoffman 1982 *Space Sci Rev* **33** 415

[12] M Temerin, J McFadden, M Boehm, C W Carlson and W Lotko 1985 *J Geophys Res* **91** 57

[13] R D Sharp, E G Shelley, R G Johnson and A G Ghielmetti 1980 *J Geophys. Res* **85** 92

[14] H L Collin, R D Sharp and E G Shelley 1982 *J Geophys Res* **87** 7504

[15] R D Sharp, R G Johnson and E G Shelley 1977 *J Geophys Res* **82** 3324

[16] D M Klumpler 1979 *J Geophys. Res* **84** 4229

[17] A D Johnstone and J D Winningham 1982 *J Geophys Res* **87** 2321

[18] F S Mozer, M H Boehm, C A Cattell, M Temerin and J R Wygant 1985 *Space Sci. Rev* **42** 313

[19] D R Dakin, T Tajima, G Benford and N Rynn 1976 *J. Plasma Phys* **15** 175

[20] D M Klumpler 1981 *Transversely Accelerated Ions in Auroral Arcs; Auroral Arc Formation*, (Geophys Monograph–25) eds. S I Akasofu and J R Kan, (Washington D C.U S A · AGU Pub) p 122

[21] N Singh, H Thiemann and R W Schunk 1987 *Planet Space Sci.* **35** 353

[22] D J Gorney, Y T Chiu and D R Croley (Jr) 1985 *J. Geophys Res* **90** 4205

[23] N Singh, H Thiemann and R W Schunk 1986 *IEEE TPS-14* 805

[24] R L Lysak, M K Hudson and M Temerin 1980 *J Geophys. Res* **85** 678

[25] P B Dusenbery and L R Lyons 1981 *J Geophys. Res* **86** 7627

[26] A M Abdalla and H Okuda 1984 *J Geophys. Res.* **89** 2235

[27] R M Winglee, P L Pritchett, P B Dusenbery, A M Persoon, J H Waite (Jr) T E Moore, J L Burch, H L Collin, J A Slavin and M Sugiura 1988 *J Geophys. Res* **93** 14567

[28] F S Mozer, C A Cattell, M K Hudson, R L Lysak, M Temerin and R B Torbert 1980 *Space Sci Rev* **27** 155

[29] R M Winglee, P B Dusenbery, H L Collin, C S Lin and A M Persoon 1989 *J Geophys Res* **94** 8943

[30] T B Moore, C J Pollock, R L Arnoldy and P M Kintner 1986 *Geophys Res. Lett.* **13** 901

[31] P M Kintner and D J Gorney 1984 *J. Geophys Res* **89** 1097

[32] H L Collin, R D Sharp, E G Shelley and R G Johnson 1981 *J Geophys. Res* **86** 6820

[33] M Temerin, H Boehm and F S Mozer 1981 *Geophys Res Lett.* **8** 799

[34] P M Kintner, M C Kelley and F S Mozer 1978 *Geophys Res Lett* **5** 139

[35] M Temerin 1986 *Geophys Res Lett* **13** 1059

[36] J Retterer, T Chong, G B Crew, J R Jasperse and J D Winningham 1987 *Phys Res Lett* **59** 148

[37] M Andre, H Koskinen and L Matson 1988 *Geophys Res Lett* **15** 107